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Sustainable biogas energy in Poland: Prospects and challenges

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ABSTRACT

The article investigates prospects and challenges for expanding of sustainable biogas energy in Poland. The number of Polish biogas fuelled power plants and installed electrical power during the 2001–2010 decade is presented. Current economical incentives for biogas energy are discussed. It is emphasized that some revisions to the Polish tradable certificate system are urgently needed in order to encourage energy crop cultivation and the use of best available power technologies. Further, promising, but mostly unexplored feedstocks, such as energy crops, grasses and sorted municipal organic wastes are analyzed. It is also revealed that agrobiogas is characterized by a unique feature of 'negative net' CO_2 atmospheric emissions and thus the role of agrobiogas in solving Polish CCS dilemmas is discussed. In regard to biogas energy systems it is stressed, that the cost of electricity from biogas is almost independent on the size of agrobiogas CHP power plants in the range of 0.2–5 MW_e. Therefore agrobiogas energy is well suited for distributed energy systems involving small-scale agrobiogas power plants offering more green jobs and improved local waste management characteristics. Finally, reliable technologies suitable for biogas energy conversion and upgrading of biogas fuel to marketable gaseous fuels are briefly characterized.

Contents

Abbreviations: AD, anaerobic digestion; CCS, carbon capture and sequestration; CHP, combined heat and power; COE, cost of electricity; GT, gas turbine; GUS, Główny Urząd Statystyczny (Polish Statistical Office); LCA, life cycle assessment; MG, Ministerstwo Gospodarki (Polish Ministry of the Economy); ORFC, oxy-reforming fuel cell; RDF, refuse derived fuel; RES, renewable energy source; TC, tradable certificate.

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1. Introduction

Biogas is a renewable and sustainable energy carrier generated via anaerobic digestion (AD) of biomass. There are at least five main biomass resources from which biogas can be derived, i.e. sewage, landfill, livestock manure, organic wastes and energy crops. Depending on its origin biogas comprises methane (40–75%), carbon dioxide (20–45%) and some other compounds, usually in trace quantities.

Biogas energy shows superior economical capacity potential among a mix of renewable energy sources (RES) in Poland [1,2]. However, the process of expanding of biogas energy is still relatively slow in Poland, compared with some other neighboring countries such as Germany [3], Denmark, Austria or Sweden.

The present article thus aims at investigation of prospects and challenges for expanding biogas energy in Poland. It is shown that key factors encouraging investment into biogas energy include (i) well-designed economical incentives (Section 4), (ii) feedstock availability (Section 6) and (iii) technological reliability (Section 9). These central drivers are characterized by in-depth discussions. Moreover, the paper emphasizes that agrobiogas energy can substantially contribute to solving Polish carbon capture and sequestration dilemmas (Section 7). Further, the optimization of the Polish biogas energy system is addressed (Section 8).

2. Climate conditions for energy crops cultivation in Poland

The climate in Poland has a transitional character between the maritime and continental climates. The typical precipitation ranges from 500 to 750 mm year^{-1}. The duration of energy crop vegetation period is around 220 days year^{-1}. Temperatures are modest and relatively stable thus daily temperature amplitudes do not usually lead to any loss in biomass crops during its growth. Another favorable factor is that Poland is mainly a lowland country. The majority of agricultural areas are located at the level not exceeding 300–350 m above the sea level and the slope gradient is not higher than 10°. This feature is favorable for bioenergy but in contrast it is highly unfavorable for hydro energy thus affecting the economical potential of bioenergy in Poland [4].

3. Deployment of sustainable biogas energy in Poland during the 2001–2010 decade

During the 2001–2005 period biogas fuelled power plants have been built in Poland only in municipal landfills and waste water treatment plants with primary objectives to limit unwanted methane emissions from landfills and to reduce the amount of sewage sludge generated by waste water treatment plants, respectively [5]. The Polish tradable certificate (TC) system designed to encourage investments into renewable energy sources (RES) has been implemented in 2005 (TC 2005). The green certificates issued according to the Polish TC system are not however technology specific, thus they have little effect on the adoption process of biogas energy in Poland. Besides, the Polish TC system offers no extra bonus for the utilization of energy crops as feedstocks for anaerobic digesters. Consequently, during the 2006–2010 period new biogas power plants still have been built mainly in landfills and municipal waste water treatment plants. In 2010 the number of all biogas fuelled power plants reached 149, and only 11 of them (7%) were agricultural biogas power plants, Fig. 1. In 2010 an average output power of all Polish biogas fuelled power plants was 0.59 MWe.

In 2008 the dominating power technology from RES in Poland was solid biomass (mainly utilized in co-combustion with coal) that achieved 84.69% share in the consumption of final energy, while biogas energy contribution was only 2.35% (landfill biogas 0.61%, waste water plants-derived biogas 1.69% and agricultural biogas 0.05%) [7]. Biogas energy has however much larger economical potential which lies, among other, in agricultural sector [3]. Table 1 presents agrobiogas fuelled power plants which have been built in Poland until 2010. It can be observed that new installed electrical power achieved 0.95 MW_e in 2005, 0.63 MW_e in 2008, 4.54 MW_e in 2009 and 2.86 MW_e in 2010. The average output power per agrobiogas power plant is 0.82 MW_e, thus it is larger than that for all biogas power plants (0.59 MW_e). The dominating feedstock is manure, organic wastes and maize silage.

4. Economical incentives for biogas energy in Poland

In order to increase the share of electricity from RES Poland introduced economical incentives in 2005. The Polish RES promotion system is based on quotas (tradable certificates (TC)). In Poland financial incentives to biogas energy currently range from 133.02 to 149.38 €MWh^{-1}, Table 2.

For small-scale biogas power plants (<0.15 MWh_e) the Polish premiums are only 49% of German premiums [3] which is unfavorable for expanding of biogas energy into a distributed renewable biopower system. Biogas fuelled power plants can also sell heat to district heating grids and biomethane to natural gas grids. The biomethane injection is to be fully regulated by law in Poland as well as the relevant system of tradable brown certificates is to be implemented.

5. Characterization of biogas derived from sewage sludge

In 2010 72% of Polish biogas was produced in waste water treatment plants from sewage sludge [7]. Below, one case study is provided in which biogas produced in Wrocław's municipal waste water treatment plant is characterized.

The Wrocław Sewage-Treatment Plant "Janówek" (WSTP) treats around 70 000 m^3 day^{-1} of municipal sewage. WSTP's biogas production amounts to around 10 000 m^3 day^{-1}. The production

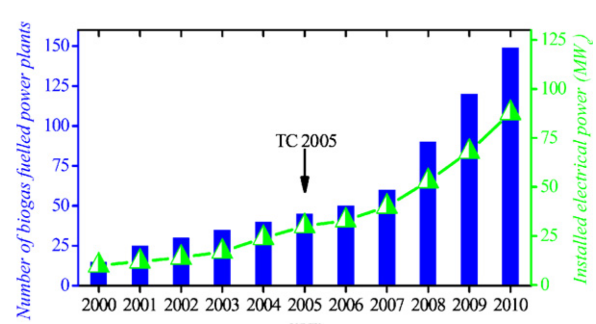

Fig. 1. The development of biogas fuelled power plants in Poland during the 2001–2010 decade [5,6].

Table 1
Agricultural biogas fuelled power plants built in Poland until 2010 [8].

Power plant	Year	Output electrical power [MW_e]	Feedstock
Pawłówko	2005	0.95	Organic mix
Płaszczyca	2008	0.63	Pig manure, silage, oil-derived wastes
Kujanki	2008	n.a.	Pig manure
Koczała	2009	2.13	Pig manure, silage, food industry derived wastes
Liszkowo	2009	2.13	Food industry derived wastes
Niedoradz	2009	0.25	Pig manure, chicken wastes
Studzionka	2009	0.03	Chicken wastes, pig manure
Nacław	2010	0.63	Manure, maize silage
Świelino	2010	0.63	Manure, maize silage, organic wastes
Kalsk	2010	1.00	Maize silage, sorgo, manure
Kostkowice	2010	0.60	Manure, organic wastes

Table 2
Financial incentives for biogas fuelled power plants in Poland according to the system of tradable certificates (TC) as of 2011, assumed $€PLN^{-1} = 4.00$ [8].

	Premiums for biogas fuelled power plants ($€MWh_e^{-1}$)	
Electrical power of biogas fuelled power plant (MW_e)	0–1	>1
Price of electricity supplied to electrical grids	49.30	49.30
Green certificates (RES)	68.93	68.93
Yellow certificates (CHP < 1 MW_e)	31.15	0.00
Violet certificates (CHP > 1 MW_e)	0.00	14.79
Total maximal premiums	149.38	133.02

Notes: Green certificates are renewable energy source (RES) premiums and apply to all biogas fuelled power plants. Yellow certificates are small-scale combined heat and power (CHP) premiums and apply for biogas fuelled power plants having electrical power smaller than 1 MW_e and involving CHP. Violet certificates are large-scale combined heat and power (CHP) premiums and apply for biogas fuelled power plants having electrical power larger than 1 MW_e and involving CHP. In near future brown certificates for biogas-to-biomethane upgrading and injection into natural gas grids is to be implemented.

facility includes two dark ADs (Fig. 2) having total volume of 13 000 m^3 which utilize a part of heat generated in downstream biogas combustion engines in order to assure the temperature of 307–309 K relevant for mesophilic micro-organisms.

Biogas is further treated for H_2S removal in a reactor utilizing activated bog ore operating according to the reaction $2Fe(OH)_3 + 3H_2S \rightarrow Fe_2S_3 + 6H_2O$. Further, biogas is purified mainly from organic sulphur compounds in an activated carbon adsorber. Finally, purified biogas is subjected to air-fuel combustion [9] and is converted into heat and electricity by means of two Jenbacher's gas engines [10] having a nominal power of 601 MW_e and 738 MW_t each. Combustion flue gases from gas engines undergo final deep oxidation by means of a catalytic converter [11] and are released into the atmosphere. Deep purification of raw biogas is needed in the WSTP due to experienced deposition of organic matter in heat exchangers of a CHP plant. The composition of municipal sewage sludge-derived biogas after its purification in the WSTP is summarized in Table 3.

Species encountered in trace quantities in the WSTP's biogas include: methanethiol, ethanethiol, acetone, benzene, toluene, xylene, acetaldehyde, chloroethane and numerous others.

6. Unexplored feedstocks for sustainable biogas production in Poland

The central issue of biogas-based power generation is the availability of cheap feedstock in sufficient quantity. There are several sources of valuable feedstock for biogas production of municipal, agricultural and industrial origin. They include sewage sludge [13], animal residues, energy crops, grasses, organic sorted wastes, landfilled wastes, etc. The development of biogas production creates an additional demand on organic feedstock, which otherwise have limited availability, thus increasing feedstock prices and enhancing the development of a feedstock market.

In Poland, the realistically available feedstock potential for the production of biogas in the by-products of agriculture and

Fig. 2. The photograph of two dark anaerobic digesters located in the WSTP (2006).

Table 3
The composition of purified biogas from the WSTP as measured over the period of 2004–2010. Concentrations recalculated to conditions: 273 K, 101.3 kPa and dry basis [12].

Component	Content	
	Range	Average
CH_4	60.2–67.7%v	63.3% (winter); 65.2%v (summer)
CO_2	32.2–39.5%v	35.7%v
N_2	0.003–0.525%v	
O_2	0–0.083%v	
H_2O	0.1–19 g m^{-3}	3.5 g m^{-3} (winter); 12.2 g m^{-3} (summer)
H_2S	0–194 mg m^{-3}	39.8 mg m^{-3}
Organic S (as H_2S)	0–140 mg m^{-3}	35.8 mg m^{-3}
Total Cl	0–40 mg m^{-3}	10.6 mg m^{-3}
Total F	0–5 mg m^{-3}	0.7 mg m^{-3}
NH_3	0–0.84 mg m^{-3}	0.13 mg m^{-3}

the agricultural and food industry amounts to approximately 1.7×10^9 m^3 biogas year^{-1} but after including energy crops it can reach 6.6×10^9 m^3 biogas year^{-1}. The Energy Policy of Poland until 2030 [14] projects that biogas fuelled power plants will be built in communes having large arable and grass lands from which biomass [15] may be generated. This constitutes a type of sustainable harmonization of the state's national agricultural priorities with those of the EU's Common Agricultural Policy [16].

Below an overview of feedstocks having great but mostly unexplored potential in regard to biogas production is provided.

6.1. Energy crops

95% of German biogas fuelled power plants use waste from crop and livestock farms such as slurry, manure and dedicated energy crops. In contrast to other countries (including Poland) where most biogas is produced using organic municipal waste, Germany relies mainly on farms for its raw material. This country has also proved the viability of producing biogas using organic waste from the food industry. The electricity production from biogas in Germany is half of that of the European Union [3].

Simon and Wiegmann [17] have shown that the Polish agricultural bioenergy sector has potential to supply 10–25% (forest and waste biomass not considered) of the total energy supply in 2030 which is even higher than that projected for Germany. De Wit and Faaij [18] have shown that the costs of biomass cultivation are substantially lower in Poland—wages are 21% of those in Germany (3.05 €h^{-1} versus 14.13 €h^{-1}), fertilizer prices are lower by more than 50% and land costs are 27% of those experienced in Germany (very suitable land: 72 €ha^{-1} year^{-1} versus 267 €ha^{-1} year^{-1} in Germany). Therefore, agrobiogas energy based on energy crops is definitely a promising energy technology from RES in Poland, at least in the perspective of next 30 years.

6.2. Grasses

In climates relevant for central EU-countries such as Poland, biogas can be suitably produced from grasses. The grass biogas system has a number of distinct advantages over other feedstocks. Firstly, grass-derived biogas does not need land use change, i.e. grass does not require arable land to grow. Grassland does not need to be plowed and planted each year, unlike maize or wheat which require annual plowing. Grass-derived biogas is also well-suited for highly urbanized areas where grassland can simultaneously perform several other social functions.

6.3. Organic wastes

Organic wastes from food industry or agriculture have great potential but they are well understood and widely adopted for biogas production. One unexplored organic waste-based feedstock relates to municipal wastes sorting. Namely, Cherubini et al. [19] have presented Life Cycle Assessment (LCA) of four municipal waste management strategies (i) landfilling, (ii) landfilling with biogas uptake, (iii) sorting and combined incineration/anaerobic digestion and (iv) direct incineration. The results of their study clearly show that a sorting plant coupled with power and biogas production plants is the best strategy for municipal waste management, since it can meet 15.47% of electricity demand and 8.24% of natural gas demand of the city of Roma. Also this third strategy has the lowest net environmental impact, quantified by global warming potential (GWP—i.e. net CO_2 emission) and acidification potential (AP—net SO_2 emission) as well as land use (net ha ton$_{waste}{}^{-1}$). Interestingly, all those three important indicators beneficially attain negative values in regard to biogas energy. According to this sustainable sorting/incineration/digestion waste management strategy (Fig. 3) valuable materials are recycled while only a minor heavy fraction of wastes is landfilled. The incineration of inorganic fraction of wastes can be achieved by combustion or gasification. The incineration of sorted wastes benefits from higher energy conversion efficiency than direct incineration of unsorted solid wastes and no drying is needed. Organic sorted wastes are efficiently converted by anaerobic digestion and further converted to electricity and heat, Fig. 3.

7. Role of agrobiogas energy in solving Polish carbon capture and sequestration dilemmas

Climate warming is attributed to the accumulation of CO_2 in the atmosphere. Anthropogenic CO_2 emissions affect the equilibria of natural carbon cycles and CO_2 concentration in the atmosphere is increasing at a rate of around 2 ppm year^{-1} currently reaching around 390 ppm. At this rate the Copenhagen Accord target of 450 ppm CO_2/+2 °C will be reached before 2040.

Polish electricity derives from coal-firing in more than 95%. Therefore, global decarbonization policy of power generation is extremely unsuitable for Poland, necessitating either the total change of the power system or the deployment of carbon capture and sequestration into coal-fired power plants. Both solutions are extremely costly and cause many additional problems.

In this regard agrobiogas has one important unique feature among a mix of renewable energy sources. Namely, through agrobiogas energy 'negative net' CO_2 emissions to the atmosphere can be achieved. In this way expanded utilization of biogas energy can offer a considerable contribution to solving Polish carbon capture and sequestration dilemmas. Budzianowski has proposed a power cycle involving biogas conversion integrated with hydrogen production and carbon capture and sequestration (CCS) [20,21]. The power cycle includes oxy-reforming of biogas and a fuel cell—oxy-reforming fuel cell (ORFC). According to the proposed ORFC cycle considerable benefits arise from enrichment of process gases in CO_2 (up to 70% CO_2) compared with air coal-firing derived flue gases comprising less than 15% CO_2. Such CO_2 enrichment can lead to considerably reduced CO_2 capture costs in the case of the ORFC cycle. Similar 'negative net' CO_2 atmospheric emissions can be achieved in biogas upgrading to biomethane processes involving, e.g. waste industrial alkaline residues as CO_2 absorbents [22].

Another important source of 'negative net' CO_2 atmospheric emission linked with agrobiogas lies in digestate utilization since it is a valuable soil fertilizer. Namely, soil fertilization by using AD-derived digestate leads to the accumulation of carbon in arable

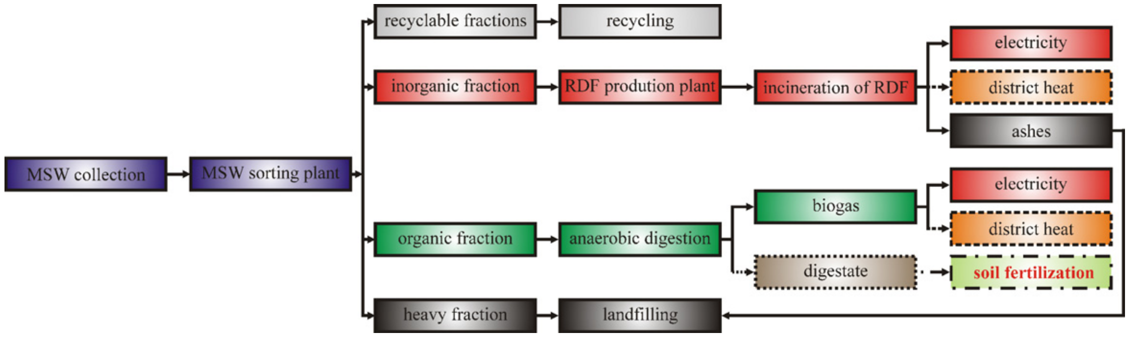

Fig. 3. The sustainable strategy for municipal solid waste management involving sorting, incineration and digestion steps.

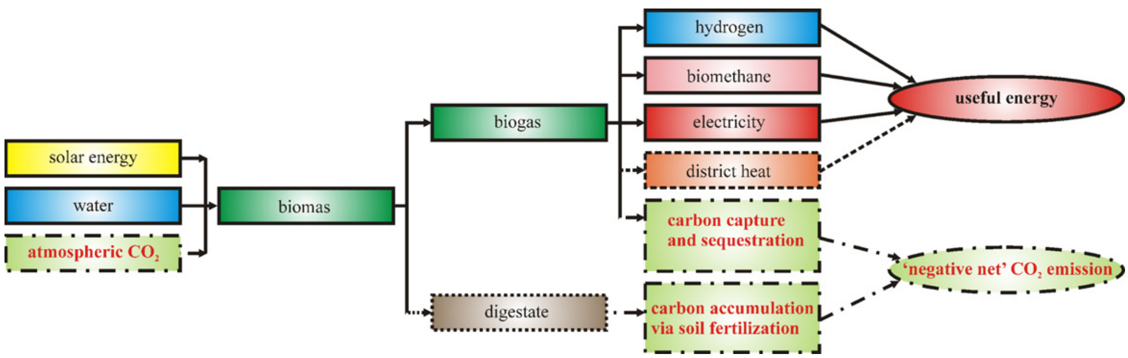

Fig. 4. The contribution of biogas energy conversion to solving global warming concerns via 'negative net' CO_2 atmospheric emission routes.

soils. Therefore, the life cycle assessment (LCA) of agrobiogas-to-CHP indicates 'negative net' CO_2 emission. Poeschl et al. [23] have reported the negative value of $-414\,kg\,CO_2\,MWh^{-1}$. This feature relates only to biogas energy and it is not characterizing any of other RES such as hydro or wind, since only biomass comprise carbon entirely assimilated from the atmosphere (because terrestrial plants are unable to assimilate non-atmospheric carbon) and only soil fertilization with digestate leads to the accumulation of atmospheric carbon into arable soils. A comprehensive explanation of 'negative net' CO_2 emission in relation to biogas energy conversion is presented in Fig. 4. It is believed that this unique feature of biogas energy can substantially contribute to solving current Polish carbon capture and sequestration dilemmas related to coal-firing.

8. Towards optimization of the Polish agrobiogas energy system

8.1. The optimal size of agrobiogas power plants

The average output power of all 11 existing Polish agricultural biogas fuelled power plants equals to $0.82\,MW_e$ (2010), which is larger than that of all Polish biogas plants (including landfill and waste water treatment plants) of $0.59\,MW_e$, as well as it is larger than the average German output power of $0.38\,MW_e$. This means that Polish agrobiogas energy system currently develops towards a more centralized direction than the German agrobiogas system. Walla and Schneeberger [24] have found that for maize silage-derived biogas fuelled CHP power plants having output power ranging from 0.20 to $5.00\,MW_e$ the costs of electricity (COE) are almost independent on the size of agrobiogas power plants (see Fig. 4 in [24]). This effect arises from the fact that the reduction of COE due to increased energy conversion efficiency of a power plant is compensated by the increase of COE due to increased maize transportation costs to ADs. Therefore, maize-based agrobiogas fuelled power plants having output power ranging from 0.2 to $5.0\,MW_e$ are characterized by similar COEs. However, small-scale agrobiogas power plants are characterized by better utilization of small-scale feedstock resources and have improved social (green jobs) and environmental (waste management) characteristics. Therefore, small-scale agrobiogas power plants can be recommended for Poland.

8.2. Revisions needed in the Polish tradable certificate system for promoting of agrobiogas energy

The Polish tradable certificate (TC) system in comparison with the German feed-in tariffs (FIT) system is less predictable. In view of the variability of economical environment and RES-related policy the valuation of future prices of TCs is characterized by large uncertainty. This uncertainty impedes the optimization of agrobiogas fuelled power plants. Investors therefore cannot calculate prospective incomes from newly proposed agrobiogas projects and thus can encounter problems with obtaining finance.

Besides, according to the current (2011) Polish RES-related law the main stream of financial support is directed to, e.g. old large-scale hydro power plants. This is costly for taxpayers and does not promote the development of new RES investments in Poland. Therefore, an urgent revision of the Polish TC system is necessary. The amendments should implement incentives being specific in regard to RES technology, should promote distributed energy system with small-scale power plants and should promote new investments by the inclusion of a depreciation criterion. Such changes are currently under development in the Ministry of Economy and their implementation will be very beneficial for the development of agrobiogas power industry. Moreover, the inclusion of energy crop and advanced technology bonuses are also needed. Those modifications will expand the deployment of agrobiogas energy and biogas-based power system will evolve towards fully distributed renewable and sustainable power system.

8.3. Summary of key factors influencing the adoption of agrobiogas energy in Poland

Table 4 summarizes main factors influencing the adoption of agrobiogas energy [25,26] in Poland for 5 most important contexts.

9. Technological reliability

Below most reliable technologies for biogas energy are discussed. Section 9.1 addresses power technologies suitable for biogas power generation while Section 9.2 characterizes technologies for upgrading of biogas to marketable gaseous fuels.

9.1. Conversion of biogas to electricity or CHP

Currently Polish biogas energy is mainly converted by using combined heat and power (CHP), with heat generated being used principally for heating anaerobic digesters and to a lesser extent the produced heat is supplied to local district heating grids. The dominating power technology is gas engine technology [10]. In Germany a technological bonus applies to four novel power technologies such as fuel cell [28], gas turbine [29], organic Rankine cycle (ORC) and Stirling engine.

9.1.1. Gas engines and gas turbines

Biogas can be burned in gas engines and be converted into mechanical and thermal energy. By using an electric generator the mechanical energy of the reciprocating gas engine is converted to electrical energy at efficiency of 29–38% being dependent on gross power. The heat produced during the operation of gas engines can be recovered in heat exchangers and supplied to thermal consumers. For large-scale biogas power plants (>60 kW_e) diesel engines are used most frequently. A diesel engine can be rebuilt into a dual fuel engine [30] or a spark ignited gas engine. The biogas/diesel dual-fuel engine can operate successfully with biogas substitution rate at above 90% by mass with no operational problems in a long-term [31]. Best biogas combustion results are achieved with lean burn gas engines. At air-fuel ratios (λ) of 1.5, NO_X and CO concentrations of less than 500 ppm can be achieved. Biogas pressure of 8–25 mbar is utilized and H_2S removal below 1000 ppm is needed.

Further, micro gas turbines are also utilized, which offer lower combustion temperatures and thus lower NO_X emissions than encountered in large-scale gas turbines. For gas turbines deeper biogas purification is needed. Produced biogas enters a compressor, which is followed by removal of moisture and then the dry compressed biogas enters an expander connected to an electric generator. The exhaust gases leave the micro gas turbines typically at 275 °C. Flue gas leaving micro turbine enters a heat exchanger to transfer its energy to the AD heating system. Flue gas exits the heat exchanger typically at 110 °C. A combined cycle gas turbines (CCGT—a Brayton cycle plus Rankine cycle) is suitable only for very large-scale biogas power plants.

External combustion is still a niche application. Namely, a Stirling engine, which is an external combustion engine (ECE), operates by cyclic compression and expansion of the working gas, at different temperature levels such that there is a net conversion of heat energy to mechanical work. ECEs are non-fuel specific, thus can utilize biogas. They require very little maintenance due to external fuel oxidation. The Stirling engines are of interest for micro-CHPs. Another ECE – steam engine – is suitable only for large-scale biogas power plants.

9.1.2. Solid-oxide fuel cells

If H_2S is removed, biogas is a valuable fuel for SOFCs [32,33]. Since biogas is a CO_2-enriched fuel carbon deposition in a reforming process and in SOFCs must be carefully avoided by applying, e.g. an increased steam-to-carbon ratio such as above 0.5 on a molar basis.

9.1.3. Technologies for thermal integration of biogas power plants

An organic rankine cycle (ORC) process can convert thermal energy from low-temperature heat sources to electricity using organic fluids of high molecular mass. The ORC system is reliable in biogas fuelled power plants with net output exceeding 300 kW_t, if high ORC's annual usage is assured.

Gas-gas heat exchangers are used for recovery of thermal energy from flue gases [34]. A key technical recommendation in biogas related heat exchanger design is to avoid sulphuric acid condensation which is highly corrosive. Sulphuric acid dew point at 50 mg SO_3 m^{-3} is 145 °C thus it is recommended to avoid cooling the gas below 180 °C and when H_2S concentration in biogas is uncertain even below 220 °C and to accept the resulting loss of heat.

9.2. Upgrading of biogas fuel to marketable gaseous fuels

Biogas fuel can also be upgraded to marketable gaseous fuels such as biomethane, compressed biogas, biohydrogen and syngas. This technological option enables to accumulate energy which is very difficult with electrical energy.

9.2.1. Biomethane

Biogas can be upgraded to biomethane (BM) and injected into natural gas grids. The treatment of biogas generally involves: (i) a cleaning process, in which the trace components harmful to the natural gas grid are removed and (ii) an upgrading process, in which CO_2 is removed to adjust the calorific value and relative density in order to meet natural gas specifications such as the Wobbe Index. After transformation, the final BM typically comprises 95–97% CH_4 and 1–3% CO_2.

Main technologies for CO_2 removal include pressure swing adsorption (PSA), high-pressure water wash (HPWW), reactive absorption (RA) [35,36], physical absorption (PA), membrane separation (MS) [37] and cryogenic separation (CS). In Europe in 2009 the dominating technologies were PSA (33 installations) and HPWW (32). The deployment of others was less popular: RA (9), PA (7), MS (7) and CS (1).

9.2.2. Compressed biogas

Compressed biogas (CB), much like natural gas, can be used to power motor vehicles such as city buses. Due to impurities biogas cleaning is usually required [38], Table 5.

9.2.3. Biohydrogen

Another alternative for biogas is a biogas-to-H_2 process for bio-hydrogen (BH) production via, e.g. water electrolysis [39]. Budzianowski has proposed one another biogas-to-electricity cycle involving a H_2 step—a decarbonized oxy-reforming fuel cell (ORFC) cycle [13]. According to the ORFC cycle biogas undergoes catalytic oxy-reforming followed by shifting to a H_2/CO_2 mixture which is then separated. The produced hydrogen is consumed in a fuel cell, which supply a part of generated electricity to water electrolysis for oxygen production. Oxygen is conveniently consumed for biogas oxy-reforming thus eliminating nitrogen dilution problem in the system.

9.2.4. Syngas

Biogas can also be upgraded to bio-syngas (BS) via reforming [40]. Syngas is then well-suited for fuel cell applications.

A summary of discussed biogas energy technologies is presented in Fig. 5. Fig. 5 emphasizes that sustainable biogas energy can supply

Table 4
Key factors influencing adoption of agricultural biogas fuelled power plants in Poland for 5 most important contexts.

Context	Factors influencing the adoption of agrobiogas in Poland
Economic incentives	TC system is not RES technology specific, no fixed tariffs are guaranteed Capital investment grants and soft loans are mostly not RES technology specific
Environmental context	6% of electricity consumption from RES (2010) Target 15% by 2020 Large GHG emission (305 Mt of CO_2 year^{-1}) [27]
Energy security	70% of natural gas supplies are from import No nuclear power (the first nuclear power plant is projected by 2022)
Agricultural context	Only 11 agrobiogas fuelled power plants but the strong support from the Ministry of Economy is observed The Polish TC system offers no premiums for the utilization of biomass in agrobiogas power plants thus energy crops cultivation is not sufficiently promoted
Technological context	Scarce scientific publications on biogas energy, especially in relation to power technologies Little technological potential in regard to anaerobic digestion and biogas-relevant energy technologies No technological bonus is offered by the Polish TC system Little involvement into national and international R&D programs

Table 5
Impacts of biogas impurities during biogas conversion.

Impurity	Impact
H_2O	Corrosion in equipment due to reaction with H_2S, NH_3 and CO_2 to form acids Accumulation of water in pipes Condensation and/or freezing due to high pressure
Particulate matter	Clogging due to deposition in equipment
H_2S	Corrosion in equipment Toxic concentrations of H_2S (>5 cm^3 m^{-3}) remain in the biogas SO_2 and SO_3 are formed due to combustion, which are more toxic than H_2S and cause corrosion with water
CO_2	Low calorific value
Siloxanes	Formation of SiO_2 and microcrystalline quartz due to combustion; deposition at spark plugs, valves and cylinder heads abrading the surface
NH_3	Corrosion when dissolved in water
O_2	Risk of explosions when highly enriched in biogas
Cl^-	Corrosion in combustion engines
F^-	Corrosion in combustion engines

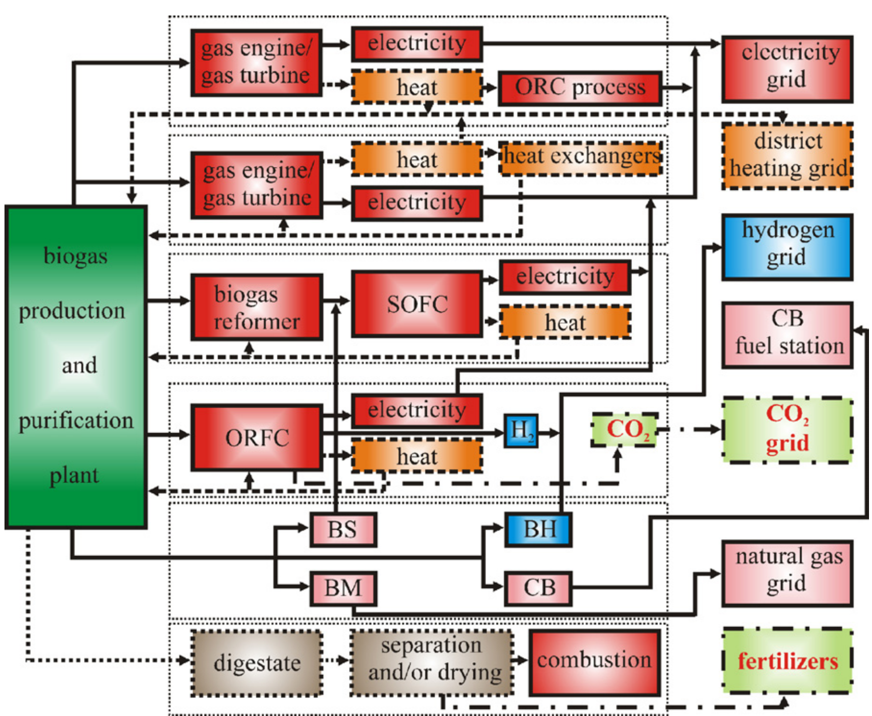

Fig. 5. The summary of (i) power technologies for biogas fuelled power plants and (ii) biogas upgrading technologies to marketable gaseous fuels.

most of final energies including electricity, heat, hydrogen, transportation fuels, natural gas as well as valuable fertilizers. Besides, it can play an important role in global warming mitigation which is extremely important feature for Poland.

10. Conclusions

From the conducted analyzes of biogas energy in Poland the following main conclusions can be drawn:

- Biogas energy is well suited for Poland in comparison with all other renewable energy sources.
- The development of biogas energy needs well-designed economical incentives promoting (i) distributed biogas energy system with small scale power plants, (ii) energy crops cultivation and (iii) the adoption of best available power technologies.
- Unexplored feedstocks for sustainable biogas production in Poland include energy crops, grasses and organic wastes.
- Agrobiogas energy can contribute to solving Polish CCS dilemmas by making use of 'negative net' CO_2 emission concept.
- Biogas energy can also stimulate development of agro-forestry communities with high degree of unemployment.

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